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Epoxy Impregnation of Ten- Stack NbTi Cables with S-2 Fiber Glass Insulation

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This study was focused on developing an epoxy impregnation technique for high field magnet program. LHC IR Quad inner cables (NbTi) were used to evaluate the process partly due to the fact that the NbTi cable was readily available at that time and partly because the first mechanical model to test the winding and impregnation process will be fabricated with this cable. The process of developing the epoxy impregnation technique involved designing a fixture to impregnate ten stack samples under vacuum, choosing an epoxy and finally developing an impregnation procedure that is repeatable and will not leave any voids within the composite.

1.0 TOOLING SETUP

A ten-stack fixture for vacuum impregnation was designed and fabricated. Fig. 1 shows the 3-D solid model of the fixture.

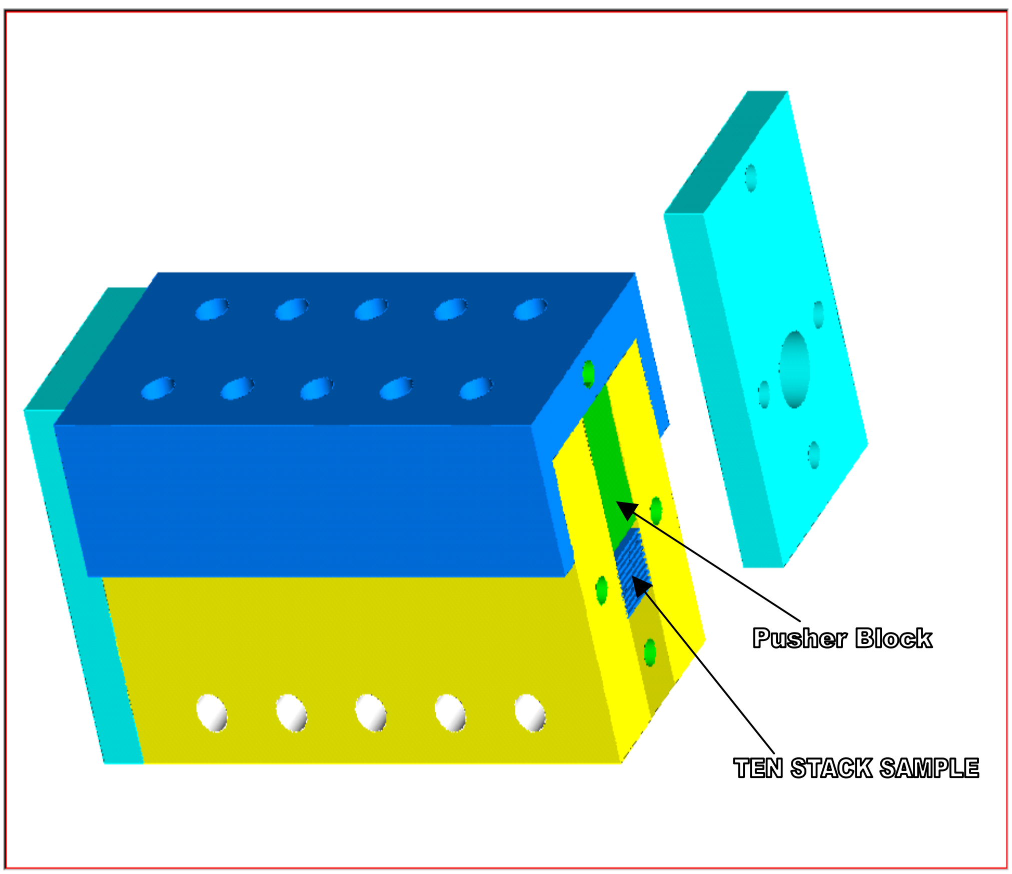

Fig. 1: *3-D solid model of the ten-stack impregnation fixture.*

The fixture was first cleaned and then mold released with RAM 225 and 334 (mixture of 50 g each). Six inch long NbTi cables were cut and wrapped with S-2 tape (butt lap). These insulated cables were then placed in the fixture as shown in Fig. 2. The height of the top pusher block was designed such that a pressure of 3000 Psi was applied on the ten stack samples while impregnation. Silicone RTV was applied on the fixture to prevent leaks. The entire fixture was then tested under helium for possible leaks.

2.0 CHOICE OF EPOXY

Two different epoxies were evaluated; (i) 828/NMA/DMP-30 which Fermilab has been using for Main Injector Magnets and (ii) CTD-101K by Composite Technologies Development Inc. Both the epoxy systems have similar resin and hardener composition but differ in the accelerator. They also have low viscosity which provides improved vacuum impregnation. However CTD-101K has longer pot-life than NMA at higher temperatures. Fig. 2 shows the viscosity Vs time at room temperature and at 60 ^{o}C for both the epoxy systems. At 25 ^{o}C, based on 5000 Cp criteria, NMA has a pot life of about 15 hrs and CTD 101K never reached this limit in 75 hrs we tested. However at 60 ^{o}C, NMA has a pot-life of only 6 hrs whereas CTD-101K has about 42 hrs. Ten-stack samples were impregnated with both the epoxy systems and quality of the impregnation was checked. The final choice will be made based on the thermo-mechanical properties of the resultant composite.

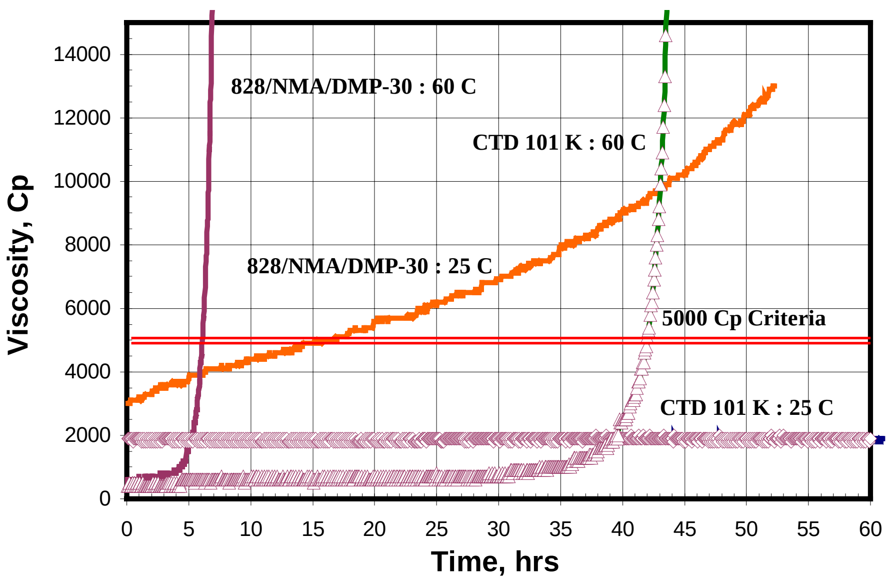

Fig. 2: *Comparison of viscosity data between CTD-101K and 828/NMA/DMP-30 at different temperatures.*

3.0 IMPREGNATION PROCEDURE

3.1 For CTD-101K

MATERIAL	DESIGNATION	PARTS BY WEIGHT
Resin	Part A	100.0
Hardener	Part B	90.0
Accelerator	Part C	1.5

Mixing Temperature: 60 ^oC

Mixing Procedure: Combine the weighted components into a container equipped with heating and mechanical stirring. Heat and stir the mixture until a clear solution at 60 ^oC is obtained.

Degas Procedure: Degas the mixture at about 50 μm of Hg for approximately 40 minutes until the bubbles evolve infrequently from the mixture. The system is now ready for application.

Fixture Temperature and impregnation: The ten-stack fixture was placed in an oven and heated to 100 ^oC in air for 30 minutes. The fixture was then taken out of the oven and wrapped in a heat-blanket. One end of the fixture was connected to a roughing pump and the other end was clamped. The fixture was then vacuumed for 30 minutes before starting the epoxy impregnation (this was done by connecting the end that is clamped to a epoxy mixture which has been degassed). The temperature of the fixture was maintained during the entire impregnation process. The process was terminated once the epoxy reached the other side of the fixture.

NOTE: It will be nice to have a fixture for the mechanical model which can be heated to 60 ^oC and can be vacuumed simultaneously.

Cure: 5 Hrs. at 110 ^oC

Post Cure: 16 Hrs. at 125 ^oC

3.2 For 828/NMA/DMP-30

MATERIAL	DESIGNATION	PARTS BY WEIGHT
Resin	EPON 828	100.0
Hardener	NMA	90
Accelerator	DMP-30	1.5

Mixing Temperature: 25 ^oC (room temperature)

Mixing Procedure: Combine the weighted components into a container and stir the mixture gently.

Degas Procedure: Degas the mixture for approximately 2 Hrs until the bubbles evolve infrequently from the mixture.

Impregnation: The impregnation set up is similar to that for CTD-101K except that the fixture is at room temperature.

Cure: 16 Hrs. at 250 ^{o}C

The setup for the vacuum impregnation is as shown below:

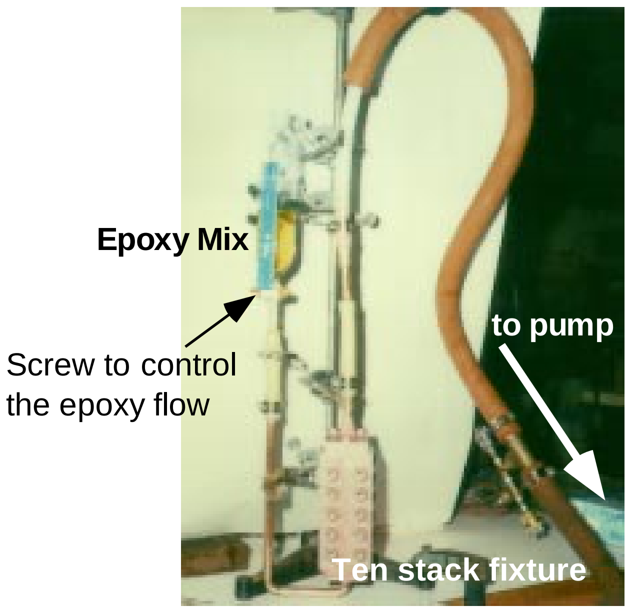

Fig. 3: *Vacuum impregnation set-up.*

4.0 RESULTS

A total of 18 samples have been impregnated. Table 1 lists all the samples along with their impregnation conditions and the quality of the impregnation. Initially CTD-101K was mixed at room temperature and degassed overnight. This technique resulted in voids on the face of ten-stack sample that faces the side-block of the fixture. Fig. 4 shows a micrograph of the edge of the ten-stack with voids. Note that when the composite was sectioned we found no voids within the composite. Two changes were made to improve the quality of impregnation. The first change was that the mixing temperature was increased to 60 ^{o}C so as to decrease the viscosity. Since the pot-life of CTD-101K is around 42 hrs, we do not foresee any problem during impregnation of the actual magnet. The second change was that the degassing of the epoxy was done only for 30 min after mixing instead of overnight. These changes eliminated the void formation in the composite. The quality of impregnation was good and its quite repeatable. Fig. 5 shows the micrograph of a the impregnated sample with no voids. Finally all the samples impregnated with 828/NMA/DMP-30 came out good without any voids.

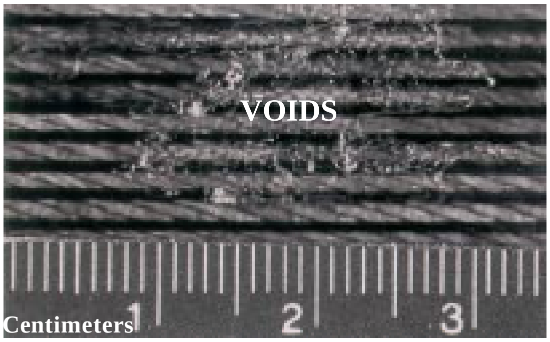

Fig. 4: *Micrograph showing edge of a sample with voids. These voids are observed between the sample and the fixture.*

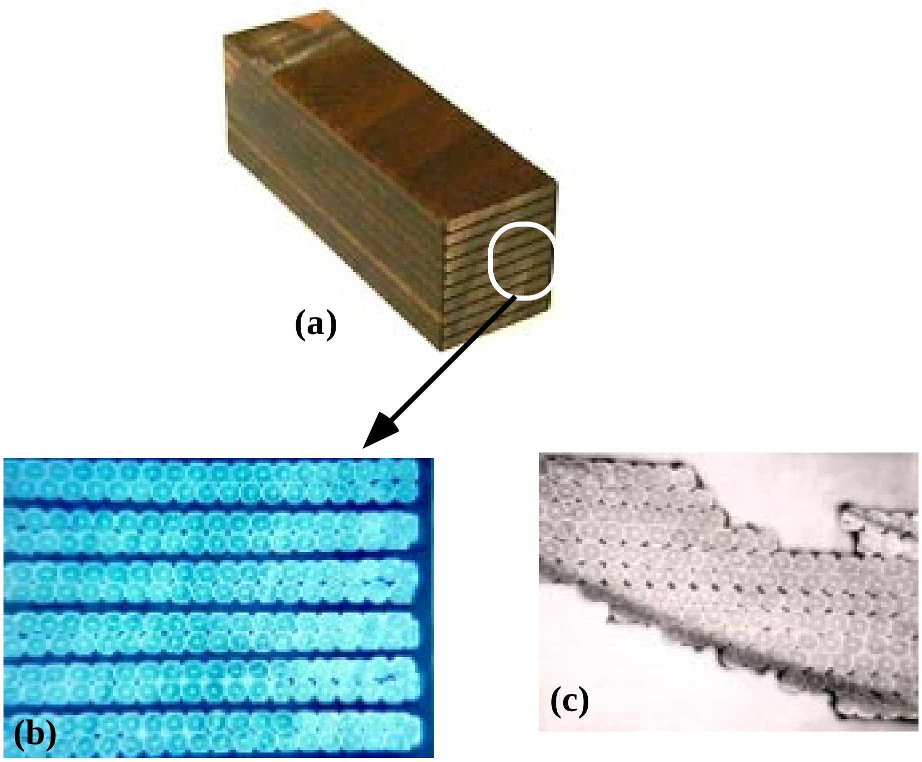

Fig. 5: *Micrographs of the impregnated samples. (a) NbTi composite with no voids. (b) cross-section of the sample and (c) cross-secion showing a thin slice of a impregnated bare cable composite used to check for voids within the composite.*

#	Material	Epoxy System	Mixing Temp.	Weight before/after (gm)	Remarks
1	Bare cable	828/NMA/ DMP-30	25 ^oC	233.2 / 240.8	Good sample with no Voids.
2	Bare cable	CTD-101K	25 ^oC	232.7 / 240.7	Voids at the interface between the fixture and the ten-stack sample. The epoxy was degassed overnight.
3	Cable + Insulation	CTD-101K	25 ^oC	252 / 261.8	Voids at the interface between the fixture and the sample.
4	Bare Cable	828/NMA/ DMP-30	25 ^oC	233.2 / 250	Good sample. Repeat of #1 with correct pressure (3000 Psi)
5	Bare Cable	828/NMA/ DMP-30	25 ^oC	233.3 / 240.8	Good sample. The sample vacuumed overnight.
6	Bare Cable	CTD-101K	25 ^oC	233.1 / 241.4	Sample procedure as #5; Voids at the interface were observed
7	Cable + Insulation	CTD-101K	25 ^oC	248.9 / 259.2	Voids were observed.
8	Bare Cable	CTD-101K	25 ^oC	232.6 / 240.2	The fixture was heated to 230 F for 4 hrs under vacuum and then impregnated. Still saw voids at the interface.
9	Bare Cable	CTD-101K	25 ^oC	232.2 / 240.9	Good sample. Back pressure of 30 Psi was applied using nitrogen after impregnation.
10	Cable + Insulation.	CTD-101K	60 ^oC	251.6 / 261.3	NO VOIDS. Also the epoxy was degassed for only 30 min instead of overnight.
11	Cable + reacted insulation	CTD-101K	60 ^oC	252 / 258.9	Good sample; no voids were observed. The fixture was checked under helium for leaks. The fixture was also heated to 100C.
12	Cable+ reacted insulation	CTD-101K	60 ^oC	250.8 / 259.2	Repeatability test. Voids were observed again at the interface. The epoxy mixture was reheated after mixing to 60 C.
13	Bare Cable	CTD-101K	60 ^oC	233.2 / 240.1	Not Good. The epoxy mixture was reheated after mixing to 60 C.
14	Cable + insulation	CTD-101K	60 ^oC	248.5 / 259.6	Not Good. The epoxy mixture was reheated after mixing to 60 C.
15	Bare Cable	CTD-101K	60 ^oC	233.8 / 240.3	Not Good. The epoxy mixture was reheated after mixing to 60 C.
16	Cable + reacted insulation	CTD-101K	60 ^oC	248.7 / 259.8	NO VOIDS. The procedure as outlined in section 3 was followed. Reheating the epoxy mixture after degassing was eliminated.
17	Cable + insulation	CTD-101K	60 ^oC	249.8 / 261.4	Repeat of # 16. NO VOIDS.
18	Cable + reacted insulation	828/NMA/ DMP-30	25 ^oC	248.1 / 259.1	No voids. The sample was impregnated to compare the mechanical properties with that of CTD-101K.

Table 1: *Development history of the epoxy impregnation process*.

NOTE: Samples 12 through 15 had voids on the side of the sample which faces the fixture. The only difference between the procedure followed for these samples and that of the samples 10 and 11 is that the epoxy was reheated after mixing and degassing to 60 ^oC. When this step was eliminated, we did not observe any voids (samples 16 and 17).